Brownian Motion Observed in Metals

Uli Dahmen and his colleagues at the National Center for Electron Microscopy (NCEM) have demonstrated Brownian motion of liquid nanoparticles inside a solid metal for the first time. The observations of very small inclusions of lead in a matrix of aluminum were made using NCEM's Analytical Electron Microscope.

Brownian motion was first observed in 1827 by Scottish botanist Robert Brown while using a magnifying glass to examine wildflower pollen grains in water. He "observed many of them very evidently in motion" and soon determined that this motion was not due to water currents or evaporation but, he thought, "belonged to the particle itself." At first he described the activity as unique to living things, but he eventually found that any sufficiently small particle, even particles of ground-up rock or glass, moved in the same way—and kept on doing so *ad infinitum*. The underlying physics behind Brownian motion was finally explained correctly by Albert Einstein in 1905. The particles are randomly set in motion as the result of collisions with the energetic molecules of the liquid. The higher the temperature, the faster the liquid molecules move, and the harder they bump into anything they encounter.

In principle, Brownian motion could be observed from liquid inclusions in a solid. In this case, it is not the moving atoms or molecules of the solid that collide with and propel the liquid. Rather, movement of atoms of solid diffuse, creating voids into which the liquid flows. In fact, in 1992 researchers at the University of Copenhagen observed rapid motion of nanometer sized globules of molten lead in solid aluminum when the system was held at temperatures above the melting point of lead (327°C) but below the melting point of aluminum (660°C). However, at the time it was not possible to follow the motion with sufficient resolution and the phenomenon could not be definitively attributed to Brownian motion.

In the subsequent decade, substantial technical progress has been in made in electron microscopes and computer-aided image analysis. A team of NCEM scientists revisited the Copenhagen experiment (in collaboration with the original researchers), using NCEM's Analytical Electron Microscope. They were able to videotape the movement of the nanosized liquid lead particles as they moved about in the solid aluminum matrix. After analyzing the videos using image-analysis software developed at NCEM, the collaborators confirmed that the phenomenon was an example of Brownian motion, that is, a thermally excited random walk. In the present case, the observed motion of liquid lead inclusions is the result of atomic-scale fluctuations of the particle shape around equilibrium. In agreement with Einstein's theory, it was found that smaller particles moved much faster than larger particles. Inclusions a few nanometers in size which can change shape easily and undergo rapid motion, while larger inclusions, a few tens of nanometers in size, were frozen in non-equilibrium indefinitely. A detailed analysis of thousands of video frames from many individual particles showed that the motion was controlled by the nucleation of steps in the aluminum at the interface between the liquid lead and the solid aluminum matrix. It was established that this nucleation barrier depends on particle size and temperature, thus explaining the enormous size dependence that is typical for the nanoworld.

There are a number of exciting questions that are still open. For example, the researchers noted circumstances when the motion was definitely not random. Some particles are attached to defects and seem to travel as a group, while smaller particles appear to repel one another. This unexpected observation is under investigation. Thus, the exotic nanoscale behavior of a seemingly unromantic metal alloy has opened a new vista of research possibilities for microscopy.

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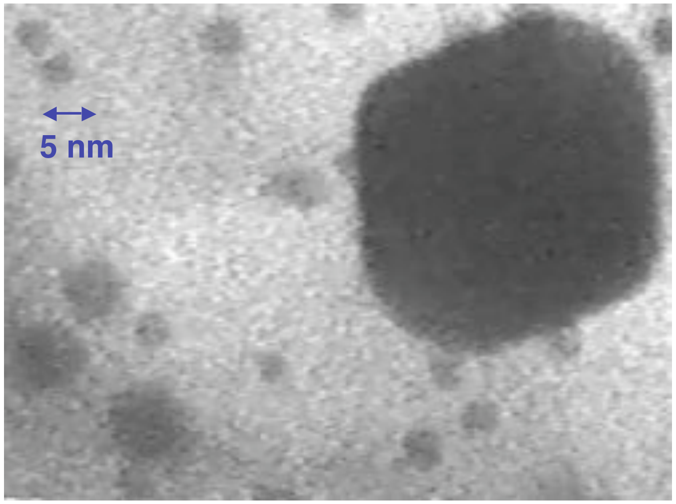
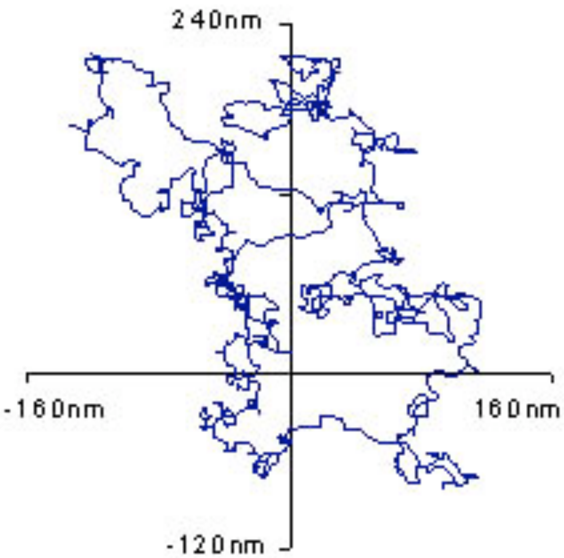
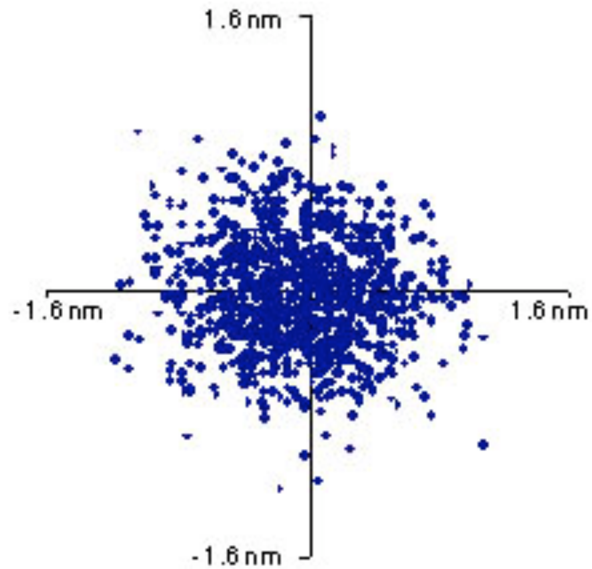


Transmission electron microscope *image of molten lead inclusions (dark) in solid aluminum matrix. At temperatures between the melting points of lead and aluminum, the small lead particles are observed to undergo rapid motion (the large particle on the right is too big to move).*



The trajectories of individual inclusions *can be followed on videotape and studied by applying the powerful image analysis capabilities of NCEM's Image Analysis Facility. The motion of the particle charted here is the classic "random walk" predicted by the theory of Brownian motion. The temperature was 436˚C (between the melting points of Pb and Al), and 1056 individual frames were analyzed.*



Scatter plot *of the motion of a single Pb particle showing that its displacement from the origin, measured at 1/30 second intervals, is random, typical of Brownian motion.*

U. Dahmen, 05-6